

IN-PROCESS ULTRASONIC EVALUATION OF SPOT WELD QUALITY

S. I. Rokhlin, S. Meng, and Laszlo Adler

Department of Welding Engineering
The Ohio State University
Columbus, OH 43210

INTRODUCTION

While spot welding has wide use in the automotive and aerospace industries there is no acceptable nondestructive testing technique for evaluation of its quality. One of the major metallurgical defects of spot welds, the stick weld, cannot be evaluated at all. There is growing interest in the industry to develop simple production-oriented nondestructive techniques for evaluation of spot weld quality.

In this paper we will discuss two ultrasonic methods for in-process evaluation of spot quality: one based on longitudinal ultrasonic waves with transducers mounted in the welder electrodes and the second based on ultrasonic Lamb waves with transducers placed on welded sheets. For comparison, both methods were used simultaneously for each weld. We will show that the Lamb wave method is more sensitive and more practical.

Preliminary results on in-process evaluation of spot welds by Lamb waves have been published elsewhere [1]. The technique used was a further development of the Lamb wave technique described by Rokhlin and Bendec [2,3] and by Rokhlin and Adler [4] and used by them for post-service evaluation of spot welds.

EXPERIMENTAL PROCEDURE

Two ultrasonic methods were developed and studied separately and simultaneously for in-process monitoring of spot welds. The first method is based on the implementation of Lamb waves. The method is schematically illustrated in Fig. 1 (a). The transmitter excites a Lamb wave in the upper sheet going toward the weld region. The joining of the sheets by welding ensures transmission of part of the incident-wave energy from the upper to the lower sheet. The transmitted energy is recorded by a Lamb wave receiver in the lower sheet. The formation and solidification of the melted pool affect transmitted Lamb wave signal which therefore carries important information on the process. The selection of the experimental conditions for Lamb wave usage were discussed elsewhere [1,2].

In the second method we used the effect of transmission of longitudinal ultrasonic waves through the weld. One homemade transducer, which serves as

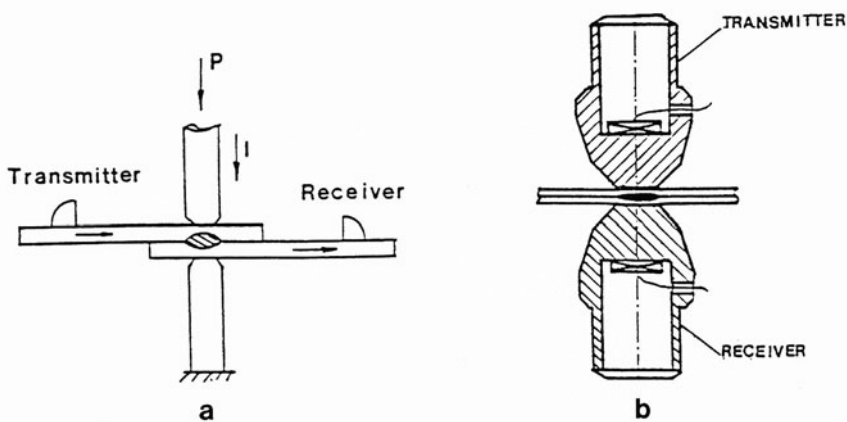


Fig. 1. Schematic illustration of implementation of (a) ultrasonic Lamb waves and (b) longitudinal waves for in-process monitoring of spot weld through weld electrodes.

the transmitter, was mounted in the upper electrode, the second transducer, which serves as the receiver, is placed in the lower electrode (Fig. 1 (b)). The amplitude of the transmitted signal was monitored during the whole welding cycle.

One of our aims was to compare these two techniques and draw a conclusion on their effectiveness for evaluation of the quality of spot welds. For this purpose both methods were used simultaneously. Lamb waves and bulk ultrasonic waves were transmitted through the melted area during welding. Two independent ultrasonic channels were used. To eliminate the effect of an acoustical coupling of the channels through the welded plates both ultrasonic generators were synchronized, separating the received signals by different time delays due to different acoustic paths. Both the received ultrasonic signals after peak-detection are digitized and fed to the computer for processing. Afterwards, the changes of the ultrasonic signals as a function of time are plotted together with the welding current on a chart recorder.

Plain carbon cold-rolled 0.045 in. thick steel sheets were used in this experiment. The weld current was the same (12 KA) for all specimens but the weld time varied from 2 to 15 cycles. Samples were in the form of two strips, each approximately 20 cm in length and 6 cm in width (length of overlap about 2 cm). Samples were prepared using an automated Taylor Winfield resistance welder (75 kVA, 60 Hz) with a programmable controller.

The spot welder was equipped with a digital data acquisition system. This system operates with three analog sensors to monitor electrode voltage, current and displacement and with ultrasonic transducers. The outputs of the sensors are digitized by a multichannel A/D converter and then stored in the microcomputer.

The shear failure load of the welded samples were measured by tensile tests. Most of the samples failed through the nugget while some of them failed through the base material (welded sheets were torn in the vicinity of the weld).

The surface of the fractured samples were studied by means of optical and scan electron microscopes (SEM). Samples were also sectioned to determine the depths of the weld (melted region) penetration. Using this analysis the diameters of the melted region, and the solid bond were determined.

Using SEM analysis the fractured surfaces of solid bonds, and stick welds, could be identified (solid bonds have continuously fractured interfaces while fractured point contacts were observed in stick weld areas). The melted region (nugget) has nearly ellipsoidal form and therefore the volume of the melted region was found as the volume of the ellipsoid $V = 4/3\pi rh$ where r is the melted region radius and h is the depth of the weld penetration (Fig. 3d).

EXPERIMENTAL RESULTS AND DISCUSSION

The ultrasonic data together with the weld current radius were recorded as functions of time during the weld period. The weld period was varied from 2 to 25 cycles of 60 Hz current. Several welds were made at each weld period. Repeatability of the results for a given weld period was very good.

Several typical records of the ultrasonic data for Lamb and longitudinal waves are shown in Fig. 2. The records of absolute value of the welding current are also shown in the figures.

The metallographical analyses of fractured weld samples showed that for two cycles, only a stick weld was formed and no melting region was observed. For three cycles only a very small melted region was found. For four cycles, both melted (in the middle of the spot) and stick (in the periphery of the spot) areas were observed. For five and more cycles, most of the spot region

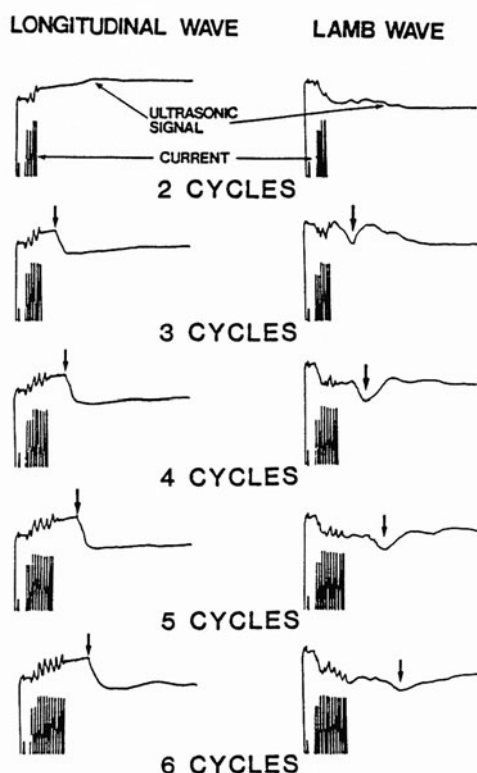


Fig. 2. Typical tracings of ultrasonic data for Lamb and longitudinal waves.

was melted with a narrow region on the periphery having a solid state bond. The stick bond corresponded to the point joints on the interface, while the solid-state bond corresponded to the joint on the continuum. The stick and solid-state bonds can be identified by scan electron microscope analyses of the fracture surfaces. The schematical model which summarizes the different stages of spot weld formation is shown in Fig. 3.

The Lamb and longitudinal ultrasonic waves are transmitted through the nugget during welding. The behavior of the pool (its melting and solidification) affects the ultrasonic signal and therefore, can be related to the different stages of the weld. Ultrasonic behavior reflects temperature changes in the pool and therefore, the ultrasonic sensor plays the role of a temperature sensor. This makes it possible to relate indirectly the changes of the ultrasonic signal to the time of cooling of the pool (nugget) to some specific temperature.

To clarify, typical ultrasonic signals for three, four and five current cycles are compared in Fig. 4. The figures are slightly shifted on the time axis in such a way that they correspond to the same moment of current termination. This moment is shown by an arrow in Fig. 4. Two sets of ultrasonic data are indicated: one for transmitted longitudinal waves, the second for transmitted Lamb waves. Sharp changes of the ultrasonic longitudinal wave trace are labelled as A. At the same time moment on the Lamb wave, trace indications (labelled B) can also be seen. Sharp minima of the ultrasonic Lamb wave signals are labelled as C. Comparison of the results for different cycles (Fig. 4) shows that the position of the minimum of the Lamb wave signal is strongly affected by the number of cycles and by the degree of development of the welding pool.

To understand the signal behavior we must take into account the metallurgical and welding process factors affecting the ultrasonic wave propagation. During the solidification of the melted pool the temperature changes from the melting point of steel (1500°) to room temperature. During the welding process the temperature of the welded region changes from room temperature to above the melting point of steel (1500°). This results in strong changes of the ultrasonic wave attenuation. It has been established

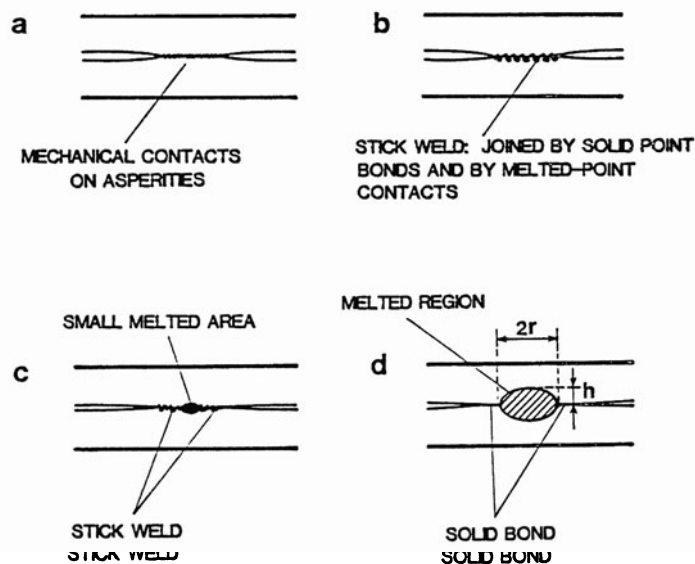


Fig. 3. Schematic illustration of different stages of spot weld formation.

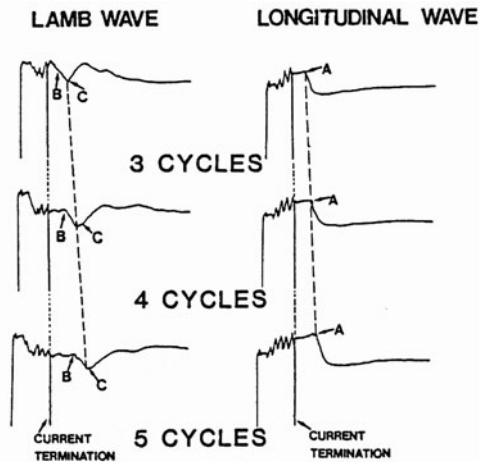


Fig. 4 Ultrasonic signal amplitudes versus time for different number of weld cycles. The plottings are shifted so that the moment of current termination for each recording corresponds to the same point on the time scale.

that the attenuation versus temperature has strong maxima at about 700° 800°C, corresponding to the α -Fe-to γ -Fe (Austenite) transformation [5]. Another maximum corresponds to the solid-to-liquid transformation (melting). The phenomena are complicated by the fact that the velocity changes also affect the behavior of the transmitted Lamb wave signal. When the temperature changes from room temperature to the melting point, the shear wave velocity changes by a factor of 1.5. Therefore, the working point on the dispersion curve for Lamb waves shifts. This looks as though the thickness of the welded plate changes by a factor of 1.5. This means that the incident mode can no longer propagate and converts to other modes before it reaches the melting region. It converts to the modes existing at the new value of the parameter $K_t h$. Elastic waves are also converted on the boundary between the liquid pool and the base material.

The maximum of the attenuation of the ultrasonic signal at the temperature of the austenite-ferrite phase transformation results in a minimum of the transmitted ultrasonic signal. Therefore, the minimum of the transmitted ultrasonic signal can be related to the temperature of this phase transformation. This is illustrated in Fig. 5 by comparison of the recording of the ultrasonic wave with the thermal modeling data [6] of the spot weld. The experimental conditions were close to the initial parameters taken for the modeling (data for 12 cycles and steel sheet thickness 1.22 mm). The minimum of the ultrasonic signal matches the transformation temperature relatively well as can be seen in the figure.

The "plateau" on the temperature curve formed immediately after welding current termination is explained by the stabilization of the fusion zone at the melting temperature. This temperature equilibrium can be related to the plateaus in Fig. 6, which shows tracings of the ultrasonic signals (from the moment of current termination to the point B for Lamb waves or point A for longitudinal waves).

The minimum of the transmitted Lamb wave signal corresponds to the same temperature for the different samples. The time of cooling from the point of current termination to this minimum corresponds to the time of welding

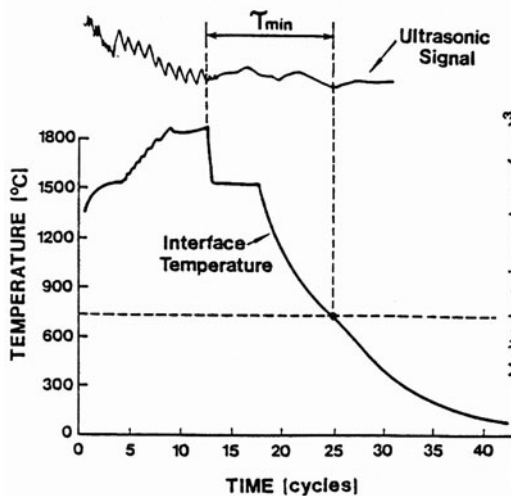


Fig. 5. Comparison of behavior of the Lamb wave transmitted signal with calculated [6] temperature changes in the spot weld.

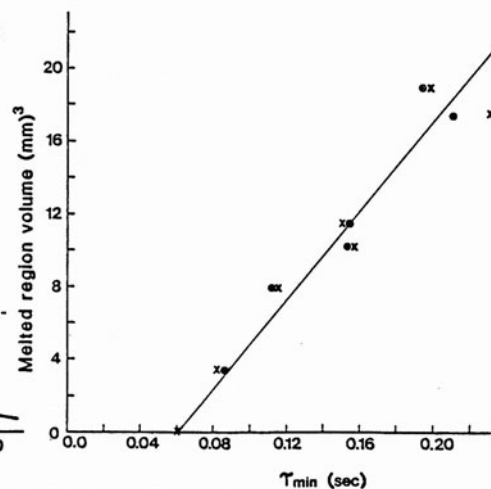


Fig. 6. The volume of the melted zone versus time shift of the minimum of the Lamb wave signal.

region cooling to this temperature. It is clear that the length of this time interval is connected to the volume of the formed liquid pool (its thermal mass), that is with the volume of the formed nugget. The larger the nugget formed, the longer the time interval. This is illustrated by Fig. 6 where the volume of the melted region is plotted as a function of the time interval from the weld current termination to the moment of the minimum of the Lamb wave signal. The comparison of the changes of the Lamb and longitudinal wave signals shows that the Lamb wave method is more sensitive to the volume of the weld pool.

One can propose that the time interval to the minimum of the Lamb wave signal can be correlated with the weld quality (weld strength). Such correlation is shown in Fig. 7. The failure load of the welds is plotted versus the length of the time interval to the minimum (τ_{min})

The shear fracture load data for different samples are plotted as a function of the spot diameter squared [4] in Fig. 8. The samples which failed through the base material are shown by triangles. The stick welds have very low fracture load. For these welds, the experimental points are indicated by open circles. Such welds correspond to a sticking of the bonded sheets without metal melting. The welds for four cycles have both stick and melted areas so both diameters are shown in this figure. It is seen from Fig. 7 that stick welds can be easily identified by the ultrasonic method discussed here. This is a very important advantage of this method because the cold weld forms good acoustic contact and therefore cannot be identified by other ultrasonic methods.

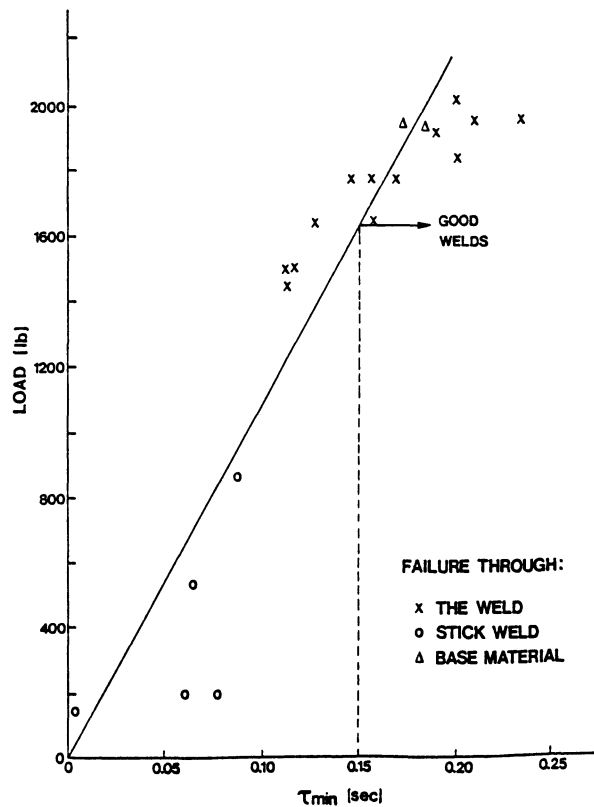


Fig. 7. Shear fracture load versus time shift of the minimum of the Lamb wave signal.

CONCLUSION

In-process testing of spot welds provides good illustrations of several advantages of in-process NDE over conventional testing after welding. The first aspect is cost: conventional NDT has a low speed of testing due to the need to position the transducer on the spot and make measurements for each single spot weld, so testing may be more time-consuming than manufacturing. This is especially important for parts with large numbers of spot welds. In-process techniques give weld quality determinations during the act of welding, in fractions of a second. The second aspect is of technical character: both conventional ultrasonic and electrical resistivity methods fail in identification of the stick weld (cold weld). This type of weld has very low strength but makes good electrical or acoustical contact and therefore cannot be identified by the above techniques. This is especially important for coated steel. The coating melts at a lower temperature than the base material. The melted coating will join sheets with excellent electrical and acoustical contact but this joint will be very weak. The in-process method resolves this problem as was shown in this paper.

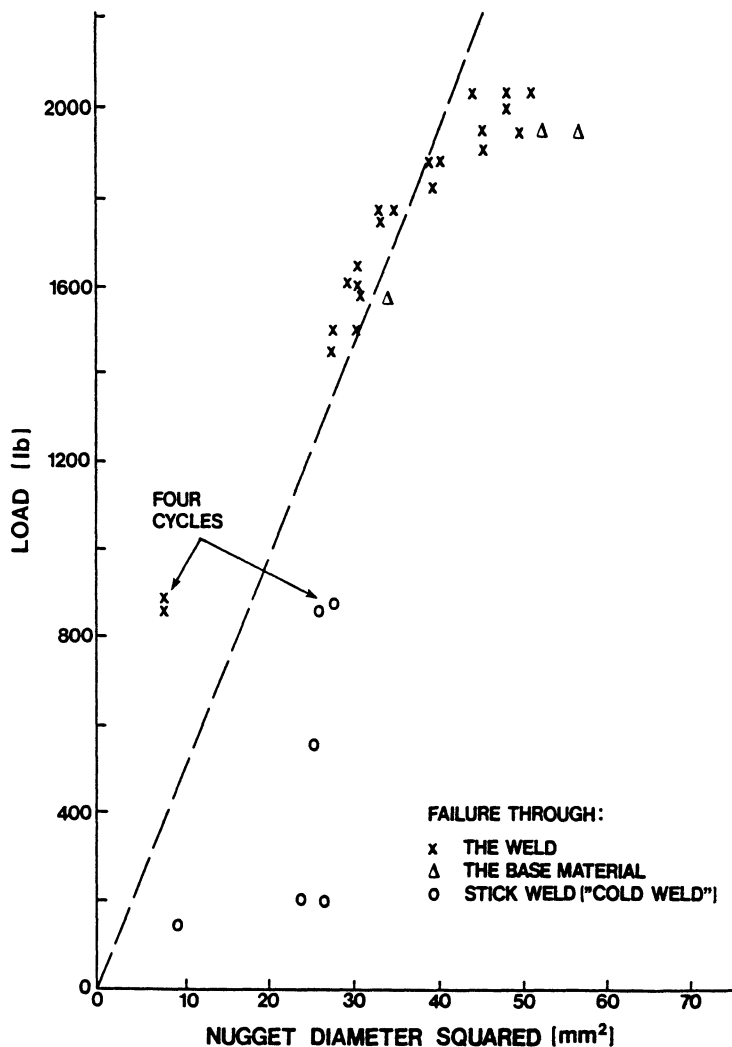


Fig. 8. Shear fracture load versus the spot diameter squared.

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